Health Monitoring of Aluminum Weldings with the Surface Response to Excitation (SuRE) Approach

I. N. TANSEL, B. L. GRISSO, G. SINGH, G. SINGH, S. KORLA and L. W. SALVINO

ABSTRACT

Recently, the impedance and Lamb wave methods were used to evaluate the integrity of welded structures. Both approaches were proven to detect defects at the other side of the welded butt joints. In this paper, the Surface Response to Excitation (SuRE) approach was used and compared with the other two methods for evaluating the integrity of the welded structures. The SuRE approach was found to be an effective structural health monitoring (SHM) tool for inspection of welded structures while yielding results similar to the other two methods. Overall, the SuRE approach is very similar to the impedance method, with the main difference being the necessity of using two transducers instead of one self-sensing actuator.

INTRODUCTION

Aluminum has been used for manufacturing light, strong and corrosion resistant parts for aerospace applications for decades. Generally, the parts were machined by removing material from a single block to obtain the desired strength in most of the aerospace applications. The heat of the welding process weakens the

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Recently, the impedance and Lamb wave methods were used to evaluate the integrity of welded structures. Both approaches were proven to detect defects at the other side of the welded butt joints. In this paper, the Surface Response to Excitation (SuRE) approach was used and compared with the other two methods for evaluating the integrity of the welded structures. The SuRE approach was found to be an effective structural health monitoring (SHM) tool for inspection of welded structures while yielding results similar to the other two methods. Overall, the SuRE approach is very similar to the impedance method, with the main difference being the necessity of using two transducers instead of one self-sensing actuator.

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strength of aluminum parts. Welded aluminum structures may develop cracks and fail quickly if they are subjected to alternating loads. The development of reliable and affordable structural health monitoring (SHM) systems is needed for large aluminum structures with welded joints to operate them confidently while reducing maintenance costs and downtime. Such structures may be used for manufacturing the next generation of ships. In this study, the feasibility of the Surface Response to Excitation (SuRE) approach is studied for detecting damage in welded aluminum structures and compared with other SHM methods.

Two of the most commonly used SHM methods evaluate the elastic behavior of the structural surface for early stage defect detection. Piezoelectric transducers provide an inexpensive and convenient tool for exciting and recording surface waves. Monitoring the electrical impedance of a piezoelectric element [1, 2] is effective at evaluating the integrity of the structures and assemblies. This method is very sensitive, and even slightly loosened bolts may be detected. Traditionally, the method requires a relatively expensive impedance analyzer, although chips are now available as an inexpensive replacement to a full analyzer. Even so, damage localization is a challenging problem for impedance techniques. The Lamb wave method excites the surface and monitors the propagation of the waves by using the same, or similar, piezoelectric element [3, 4]. Lamb wave techniques provide more practicality for localizing and characterizing any detected damage. Recently, both approaches were successfully used for monitoring the health of welds and the structure across welded connections [5].

One of the low cost alternatives to using an impedance analyzer is applying a swept sine wave generated by a spectrum analyzer to one surface bonded piezoelectric transducer and monitoring the response at another piezo. The spectrum analyzer samples the response and calculates the magnitude of the transfer function between the two piezos [6-8]. This approach requires an additional piezoelectric element when compared with the impedance method. However, the cost of spectrum analyzers is generally half of the comparable impedance analyzers.

The performance of the SuRE method for inspecting welded joints was studied in this paper and compared with the other two methods. In the following sections, the theoretical background, experimental procedure, results and the conclusions are presented.

THEORETICAL BACKGROUND

To evaluate the similarity of the magnitudes of two frequency response signals, the sum of squares of the differences may be calculated. The sum was calculated with the following equation in this study:

$$E = \sum_{i=1}^{n} \left(M_{j,i} - M_{r,i}\right)^2 \qquad (1)$$

$M_{j,i}$ is the magnitude of the considered transfer function of the j^{th} data set, and $M_{r,i}$ is the magnitude of the reference signal. The square of the differences are calculated at n different frequencies. i is the index from 1 to n. The magnitude observed for the healthiest case with minimum defects was used as the reference. The sum of the square of the differences (E) is zero if the test and the reference cases are exactly the same. E indicates how much the magnitude characteristics of the test case are different from the reference signal.

EXPERIMENTAL PROCEDURE

For experimental data collection, two 5083-H116 aluminum plates (3x3x0.25inch) were welded together with a butt joint (Figure 1). Three piezoelectric transducers were attached to the surface with Vishay Micro-Measurements M-Bond 200 adhesive. The diameter and thickness of the piezoelectric transducers (851 material from APC, International) were 0.5 inch and 0.02 inch respectively. One of the transducers (the upper one at the right hand side) was excited while the other transducers were used as the receivers/sensors. The picture of the welded plates is presented in Figure 1. Damage was progressively introduced starting with a 1/8 inch vertical cut in the top of the weld. Later, the length of the cut was increased to 1/4 inch. After the cuts, three holes with 1/16 inch diameters were drilled at three different locations. The holes and their location may be seen in Figure 1. A Stanford Research Systems (SRS) –SR780 spectrum analyzer was used to generate the sweep sine wave, acquire the data, and calculate the magnitude relationship between the excitation and the output of the sensing piezoelectric transducer.

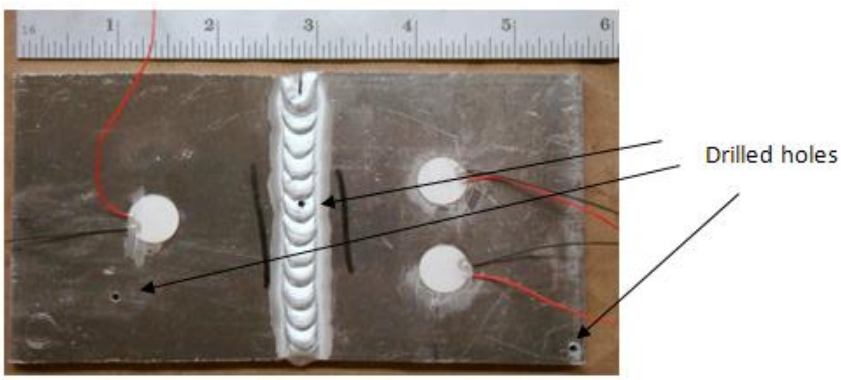
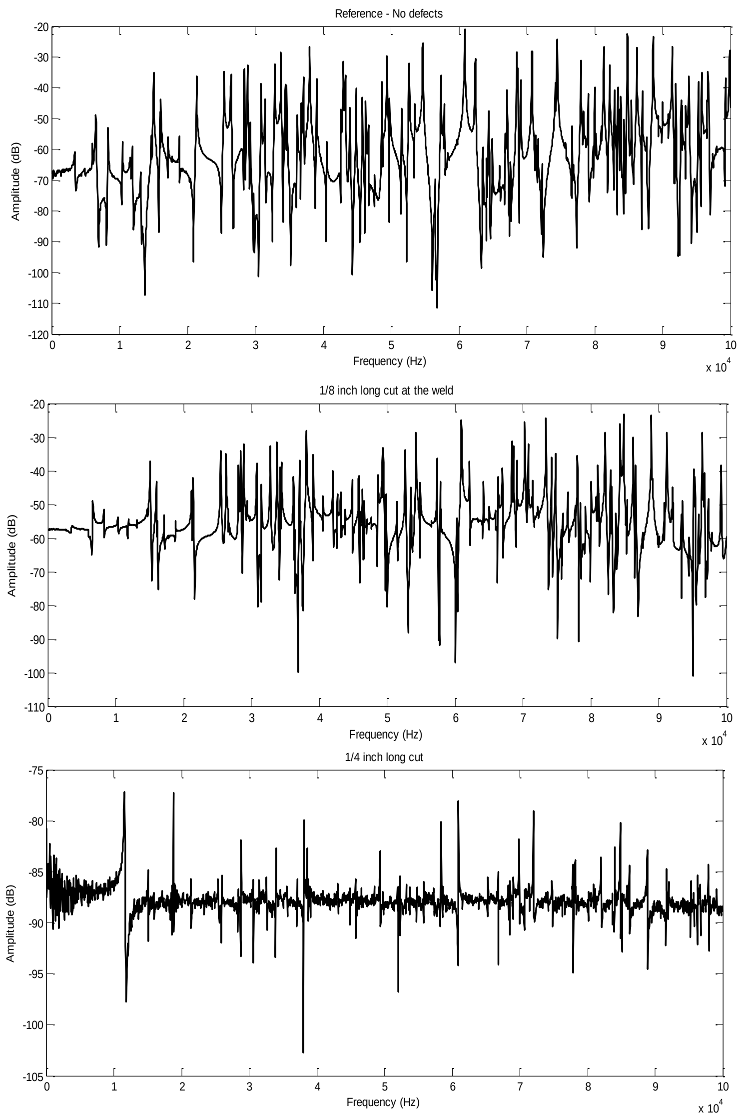


Figure 1. The welded plates prepared for the test. A ¼ inch cut is seen at the top of the weld, along with three 1/16 inch diameter through holes.

RESULTS AND DISCUSSION

The magnitude of the frequency response of the plate was determined by using the SuRE approach and presented in Figure 2a. The characteristics of the magnitude changed significantly when the 1/8 inch long cut was created on the weld (Figure 2b). The observed frequency response changed again when the cut was extended to ¼ inch (Figure 2c).



(a) Without any cut

(b) With 1/8 inch long cut

(c) With 1/4 inch long cut

Figure 2. The magnitudes of the transfer functions calculated by the SuRE approach.

The difference was easily represented by using the sum of the squares of the differences of the frequency responses. The bar graph in Figure 3 indicates that the baseline characteristics were very similar when there was not any damage (two at the left). The following four of bars indicate that the characteristics of the magnitude changed when the 1/8 inch long cut was created (middle two) and extended (right two). In both cases, the characteristics of the signals were very repetitive as long as the experiments were repeated at the same conditions.

The SuRE approach was performed to detect drilled holes at different locations of the aluminum plates and the joint. The SuRE detected the first hole located at the middle of the weld with a 1/16 inch diameter very clearly (Figure 4 top). The sum of the squares of the differences (Figure 4 bottom) increased when the second and third holes were drilled to the left and right plates with the same diameters. To demonstrate the similarity of the observed magnitudes at the same conditions, the experiments were repeated multiple times and two of the collected data were used for each case at the bar graph.

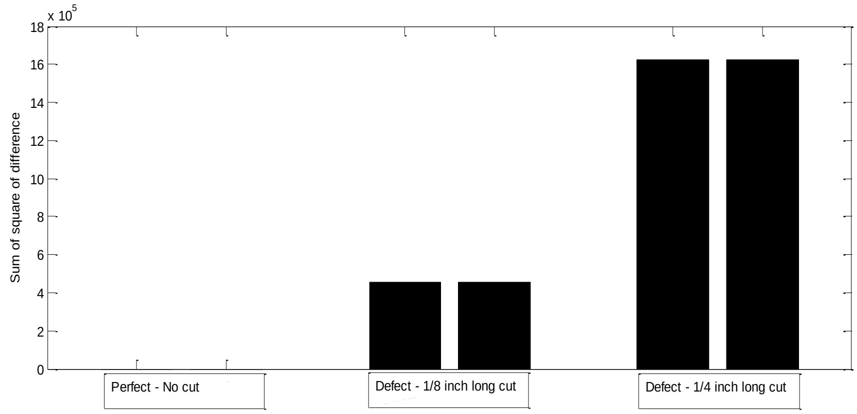


Figure 3. The sum of the squares of the differences of the frequency responses in Figure 2.

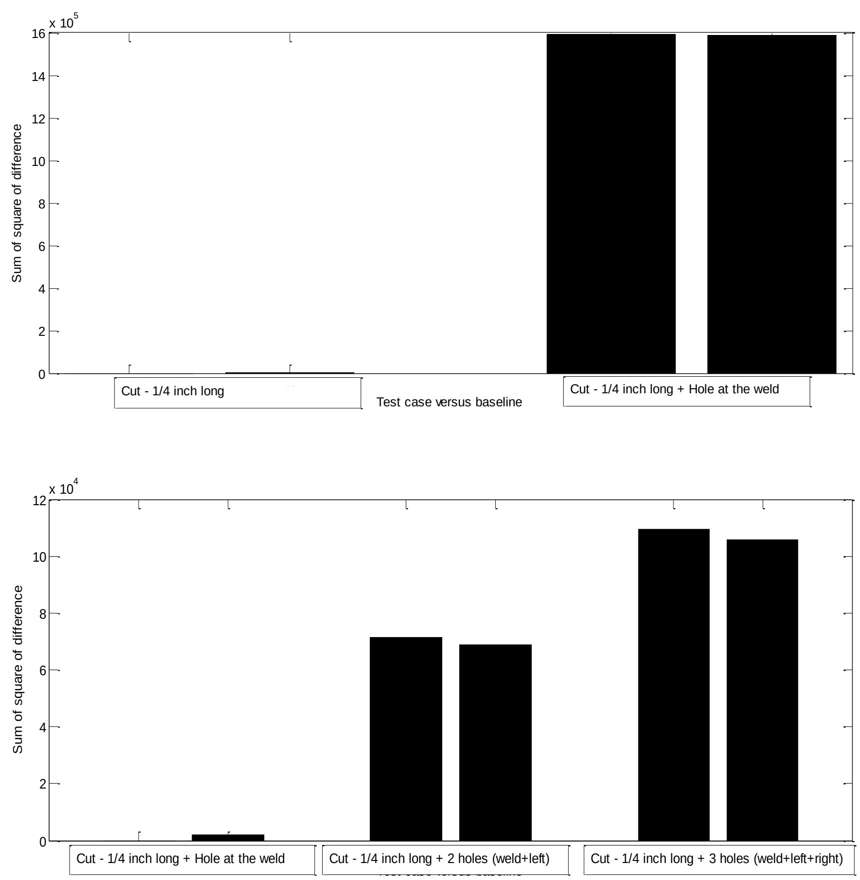


Figure 4. The sum of the squares of the differences of the frequency responses when the hole at the welded joint (top) and the other two holes (bottom) were drilled.

The variation of the sum of the squares of the differences were calculated by using the impedance method and presented in Figure 5 before and after the hole on the left plate was drilled. The SuRE and impedance approach use the frequency response characteristics of the signal, and measurements were analyzed conveniently by calculating the sum of the squares of the differences. The magnitude of the surface response and real part of the mechanical impedance are in the frequency domain. Both approaches are very sensitive to the changes created at the surface response characteristics either by the defects or compressive forces. The envelopes of the Lamb wave approach is presented in Figure 6 before the hole damage and with one and two holes. The characteristics of the envelopes changed when the holes were present. The envelopes were in the time domain, and the analysis of the results requires more complex approaches.

The SuRE, impedance and Lamb wave analysis methods were able to detect the defects located on the weld. In addition, they were capable to sense the holes on a plate without any excitation and sensor as long as it was attached to another plate with proper transducer(s) with a significantly large weld.

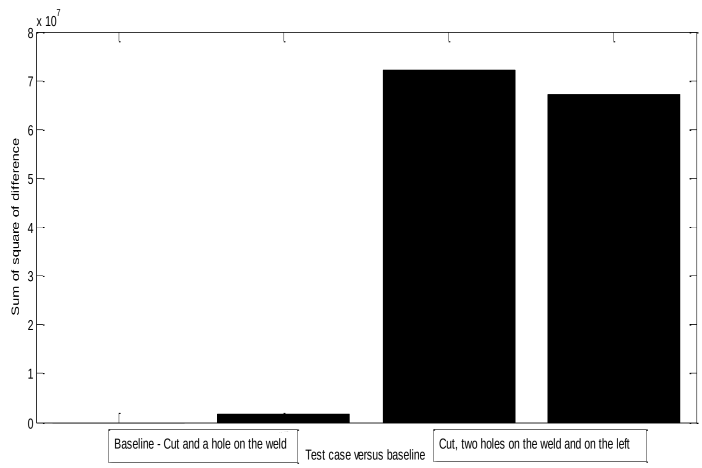


Figure 5. The impedance method was used to detect the hole on the left plate.

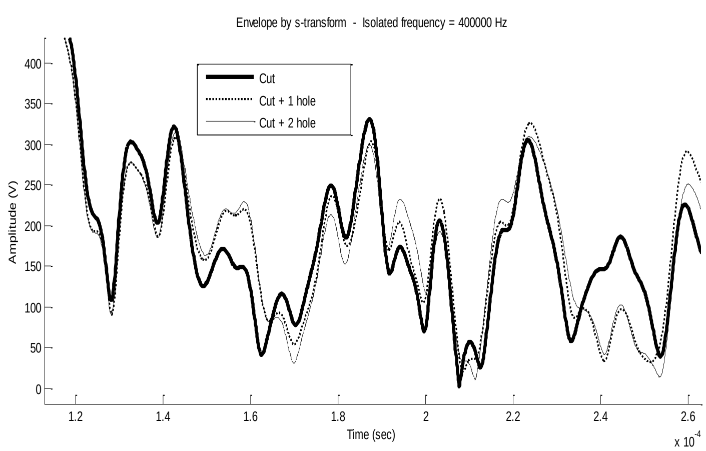


Figure 6. The Lamb wave approach. The envelope changed when the first two holes were drilled.

CONCLUSIONS

The performance of the SuRE approach was tested for detecting defects on and beyond the welded joints. Two aluminum plates were welded with a butt joint, and piezoelectric transducers were bonded to their surfaces. The SuRE approach was used to detect cuts in the weld and three additional holes. The magnitudes of the surface responses estimated by the spectrum analyzer were compared by calculating sum of the squares of the differences.

In the study, the SuRE approach detected all the considered defects to and through the weld. The cuts on the weld made the most significant change to the magnitudes of the surface response. The first hole was also very detectable but it was less than the effects of the cuts. The frequency responses changed slightly due to the second and third holes, but were still observable as damage in the bar charts comparing the transfer function magnitudes.

The SuRE and impedance methods use the magnitude or real part of the frequency domain transfer functions. The envelopes calculated for the Lamb wave method are in the time domain. This study found the characteristics of the SuRE approach are closer to those of the impedance method. Similar to the impedance and the Lamb wave method, SuRE detected the defects beyond the weld. We could detect a hole drilled on one of the test plates without using the transducer(s) on the same plate.

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